ZENER-BLOCH OSCILLATIONS

- It was first observed by ***Bloch*** and ***Zener*** while examining the electrical properties of crystals.
- **Definition*:*** A particle in a periodic potential with an additional constant force performs oscillations and these oscillations are called ***Bloch oscillations***.
- **Definition:**The dynamics of quantum particles shows a coherent superposition of Bloch oscillations and Zener tunneling between the sub-bands which is called as **Zener-Bloch oscillations.**
- It is very difficult to observe Bloch oscillations in natural crystals. This is due to the scattering of electrons by lattice effects.

Derviation

The one – dimensional equation of motion for an electron in a constant electric field is

$$\mathrm{F} = \frac{\mathrm{dp}}{\mathrm{dt}} = \hbar \frac{\mathrm{dk}}{\mathrm{dt}} = -\mathrm{eE} \qquad ----(1)$$

The solution of equation (1) is

$$\mathrm{k(t)} = \mathrm{k(0)} - \frac{\mathrm{eEt}}{\hbar} \qquad ----(2)$$

The position of the electron *'x'* is given by

$$x(\mathrm{t}) = x(0) - \frac{\mathrm{A}}{\mathrm{eE}} \cos\left(\frac{\mathrm{aeE}}{\hbar}\mathrm{t}\right) \qquad ----(3)$$

Equation (3) shows that the electron oscillated in real space.

From equation (3), the angular frequency of the oscillations is given by

$$\omega_{\mathrm{B}} = \frac{\mathrm{ae|E|}}{\hbar} \qquad ----(4)$$

Use: The Zener Bloch oscillations can be used for the construction of a matter wave beam splitters.

RESONANT TUNNELING

Definition:

It refers to tunneling in which the electron transmission coefficient through a structure is sharply peaked about certain energies.

- An interesting phenomena occurs when two barriers of width ‘a’ separated by a potential well of small distance ‘L’ .
- This leads to the concept of resonant tunneling.
- The barriers are sufficiently thin to allow tunneling and the well region between the two barriers is also sufficiently narrow to form discrete (quasi bond) energy levels.
- The analysis of the double barrier structure is essentially the same as considered for single barrier tunneling.
- The transmission coefficient of the double symmetric barrier becomes unity (i.e., T = 1), when the energy of the incoming electron wave (E) coincides with the energy of one of the discrete states formed by the well.

$$\text{i.e.,}\, E = E_n = \frac{n^2h^2}{8m_eL^2} \qquad \text{where,}\, n = 1,2,3 \ldots$$

- Resonant tunneling is the basic of a number of electronic devices.
- Double barrier tunnel has important applications to a device known as a ***resonant tunneling diode***.

QUANTUM INTERFERENCE EFFECTS

Definition:

A physical phenomena when two or more particles that are space and time independent have an interaction,constructing of destructing their wave functions is known as ***quantum interference***.

- Quantum interference is one of the most challenging principles of quantum theory.
- Basically, the concept states that elementary particles cannot only be in more than one place at any given time (through superposition), but that an individual particle,

such as a photon (light particles) can cross its own trajectory and interfere with the direction of its path.

- In nineteenth century, Thomas Young devised the double-slit experiment to prove that it considered of waves.
- The noted physicist Richard Feynman claimed that the essentials of quantum mechanics could be grasped from an exploration of the double slit experiment.
- According to Feynman, each photon goes through both slits and also simultaneously traverses every possible trajectory on the way to the target.
- ***Applications:*** Quantum interference research is being applied in a growing number of applications, such as the superconducting quantum interference device (SQUID), quantum cryptography and quantum computing.

MESOSCOPIC STRUCTURES

- ‘Nano’ means precisely small, ‘meso’ is a broader term, which means intermediate between the microscopic (molecular) and macroscopic (bulk) scales.
- **Definition*:*** The prefix “meso-” means “in between” or “intermediate”. Mesoscopic systems are those that are larger than atoms and yet very much smaller than the large scale every day object that we can see and touch.
- A macroscopic device, when scaled down to a meso-size, starts revealing quantum mechanical properties.

Difference between macroscopic level and microscopic level

- At the macroscopic level the conductance of a wire increases continuously with its diameter.
- However, at the mesoscopic level, the wire’s conductance is quantized i.e., the increases occur in discrete or individual, whole steps.

Mesoscopic Devices

- During research, mesoscopic devices are constructed, measured and observed experimentally and theoretically in order to advance understanding of the physics of insulators, semiconductors, metals and superconductors.

- **Importance of mesoscopic system**

1. They have different physical and chemical properties.
2. They can make computers, sensors and other devices with different properties.

Example for mesoscopic systems

1. The molecules in our bodies that break down the foods in our stomachs and intestines and the molecules that carry oxygen from the lungs to other parts of the body are nothing but nanoscale machines.
2. Artificial nanostructures, such as multilayered nanostructures, made up of thin mesoscopic layers of different materials, have been used in devices such as high-efficiency lasers and light emitting diodes (LEDs).

CONDUCTANCE FLUCTUATIONS AND COHERENT TRANSPORT

Conductance Fluctuations.

- **Definition*:*** During electron transport, if the coherence length of electrons is larger than the momentum relaxation length, electrical fluctuation occurs. The occurrence of electrical fluctuations during the electron transport is called ***conductance fluctuations***.
- The mesoscopic structures consist certain defects or impurities which cause in scattering or interference effects.
- This results in the change of the flow of electrons. There are several reproducible fluctuations in the mesoscopic interference for the electron transport.

Coherent Transport

- **Definition:** the transport of particles in a given dimension with coherence in space and time which is similar to the guided wave is known as ***coherent transport***.
- The word coherence in optics means that the amplitude, frequency for the particle or group of particles is same.
- The coherence is space dependent and time dependent.

- In the context of nano or mesoscopic structures, the contact force changes the fundamental particle owing to the dimensions.
- This inturn triggers the other entire particle to rearrange themselves. Due to the dimensions these fundamental particles follow certain coherence in space and time.
- This further makes all the particles to be transported along a given dimension of the material in a same way.
- This is referred to as the coherent transport of particles in a given dimensions and is somewhat similar to the guided wave.

COULOMB BLOCKADE EFFECTS

- ***Definition:***The resistance to electron transport caused by electrostatic coulomb forces in certain electronic structurs, including quantum dots and single electron transistors is called ***Coulomb Blockade***.
- In other words, the prohibition or superposition of tunneling is called ***Coulomb Blockade***.
- In simple words, the suppression of electron flow is called ***Coulomb Blockade***.

Explanation

- In the case of a quantum dot, the charges are all negative electrons.
- Trying to bring them forcefully together create coulomb forces.
- It is a well known fact that the isolated droplet of electrons does not willingly accept another, but repels it.
- This is Coulomb blockade and it helps prevent constant tunneling to and from a quantum dot.
- Now we can measure the Coulomb blockade effect.
- A quantum dot has a capacitance, 'C_{dot}', a measure of how much electric charge it can store.

$$C_{dot} = G\varepsilon d \qquad ---- \ (1)$$

Where,

ε → Permittivity of the material surrounding the dot

d → Diameter of the dot

G → Geometrical term (If the quantum dot is disk, G = 4, if it is spherical particle, G = 2π)

- The energy needed to add negatively charged electron to the dot is known as the charging energy, E_C. It can be derived as

We know, $q = CV$ and $e = CV$

$$\therefore V = \frac{e}{C}$$

$$\therefore E = \frac{1}{2}CV^2 = \frac{1}{2}\frac{e^2}{C}$$

$$\therefore E_C = \frac{e^2}{2C_{dot}} \qquad ----\ (2)$$

Where, *e* → Charge of electron

Inference

- From equation (2), we can see that E_C is inversly proportional to the dot,s capacitance.
- In that case, al large capacitor can quite easily accommodate another electron without too much energy required.
- However, in the opposite case, with extremely small capacitors (quantum dots), the charging energy can be substantial (large). That is, small capacitors (quantum dots) are large enough to "block" tunneling electrons.

Energy required

- Now, we have to know how much energy is necessary to block the tunneling electrons in the coulomb blockade.
- Coulomb blockade needs more energy than a given electron can "spend" trying to tunnel in and out.
- The coulomb blockade can prevent tunneling, when the charging energy is much higher than the thermal energy of an electron.

Condition for coulomb blockade

- The condition of the coulomb blockade is therefore

$$\mathrm{E_C > K_B T} \qquad \text{where, } \mathrm{K_B} \rightarrow \text{Boltzmann constant} \quad \mathit{and} \quad \mathrm{T} \rightarrow \text{Temperature}$$

- As a rule of thumb, $\mathrm{E_C > 10K_B T}$. this criterion can be more easily achievable if smallere the dot becomes.